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Stephen C. Butler et al

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Undersea Warfare Center
Division Newport
1176 Howell Street, Code 00L, Bldg. 102T
Newport, RI 02841

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9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Naval Undersea Warfare Center
Division Newport
1176 Howell Street, Code 00L, Bldg. 102T
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14. ABSTRACT
A method for designing an acoustic array includes establishing a desired beam pattern, acoustic wavelength and beamwidth for the array. Geometric parameters are calculated from these constraints. The array is modeled as a plurality of elements positioned in accordance with the geometric parameters. An amplitude shading function is calculated. An array of acoustic elements is constructed having an area calculated from the calculated amplitude shading function. An acoustic array designed by this process is further provided.

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DEPARTMENT OF THE NAVY
OFFICE OF COUNSEL
NAVAL UNDERSEA WARFARE CENTER DIVISION
1176 HOWELL STREET NEWPORT RI 02841-1708

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TECHNOLOGY PARTNERSHIP ENTERPRISE OFFICE
NAVAL UNDERSEA WARFARE CENTER
1176 HOWELL ST.
CODE 00T2, BLDG. 102T
NEWPORT, RI 02841

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Inventor	Stephen C. Butler et al

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METHOD FOR DESIGNING AN ACOUSTIC ARRAY

STATEMENT OF GOVERNMENT INTEREST

[0001] The invention described herein may be manufactured and used by or for the Government of the United States of America for governmental purposes without the payment of any royalties thereon or therefor.

CROSS REFERENCE TO OTHER PATENT APPLICATIONS

[0002] None.

BACKGROUND OF THE INVENTION

(1) Field of the Invention

[0003] The present invention is directed to a method for designing an acoustic array and more particularly to a method for designing an acoustic array with simplified wiring and processing.

(2) Description of the Prior Art

[0004] Beamforming is used in active and passive sonar to increase the efficiency or gain from an array of transducers. In such an array, each transducer is separately wired to acoustic processing equipment. The acoustic processing equipment adjusts the power and time delay associated with the joined transducer. This requires separately controlling the signal associated with each array element.

[0005] Conventional arrays modify beam patterns to lower sidelobes by electrically shading the outputs of a number of elements, or less effectively, by using multiple elements in a series parallel connection. It is known that types of hydrophones, such as PVDF hydrophones, can be shaped so as to achieve the same, reduced sidelobe levels as a number of electrically shaded elements thereby eliminating the electronics and saving space. It has been shown that a single element can be shaped as a linear tapered element or an element shaped to an approximation of a -40 dB Chebyshev shading function can be used to reduce the sidelobes from that which would be expected with a rectangular element. These single elements are mounted to a cylindrical surface before use. These methods teach suppression of sidelobes by area shading, but they don't teach a method for designing an acoustic transducer or sensor to a preferred beam pattern.

[0006] Curved and doubly curved geometries are known for active and passive sonar arrays; however, in the prior art, the array shape is dictated by the underlying object, not the beam pattern. Electronic shading is typically used for giving a preferred beam pattern. One such array is given by U.S. Patent No. 6,711,096 to Kim C. Benjamin. Also known are methods for making arrays having conforming shapes such as that given in U.S. Patent No. 6,255,761 to Benjamin.

SUMMARY OF THE INVENTION

[0007] It is a first object of the present invention to provide a method for designing acoustic arrays in accordance with a preferred beam pattern;

[0008] Another object is to design acoustic arrays that minimize the use of processing and electronics to achieve the desired beam pattern; and

[0009] Yet another object is to provide an acoustic array having a beam pattern that conserves power by avoiding projection of acoustic energy in undesired directions.

[0010] Accordingly, there is provided a method for designing an acoustic array that includes establishing a desired beam pattern, acoustic wavelength and beamwidth for the array. Geometric parameters are calculated from these constraints. The array is modeled as a plurality of elements positioned in accordance with the geometric parameters. An amplitude shading function is calculated. An array of acoustic elements is constructed having an area calculated from the calculated amplitude shading function. An acoustic array designed by this process is further provided.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] Reference is made to the accompanying drawings in which are shown an illustrative embodiment of the invention, wherein corresponding reference characters indicate corresponding parts, and wherein:

[0012] FIG. 1 is a diagrammatic view of a curved line array;

[0013] FIG. 2 is a model of the curved line array of FIG. 1 using discrete points;

[0014] FIG. 3 is a beam pattern generated by an array such as that given in FIG. 2;

[0015] FIG. 4 is a desired beam pattern for designing an array according to the current invention;

[0016] FIG. 5 is a graph of desired weightings versus angles for designing an array according to FIG. 4;

[0017] FIG. 6 is a graph of the resulting beam pattern from the weightings given in FIG. 5;

[0018] FIG. 7 is a top view of a first embodiment of a continuous array in accordance with the weightings given in FIG. 5;

[0019] FIG. 8 is a cross-sectional view of the continuous array given in FIG. 7;

[0020] FIG. 9 is a top view of a second embodiment of a discrete array in accordance with the weightings given in FIG. 5;

[0021] FIG. 10 is a cross-sectional view of the dicrete array given in FIG. 9;

[0022] FIG. 11 is a three-dimensional diagram of an array such as that given in FIG. 9 having elements along two dimensions;

[0023] FIG. 12 is a three-dimensional diagram of an alternative embodiment of an array such as that given in FIG. 11 having elements along two dimensions; and

[0024] FIG. 13 is a three-dimensional diagram of an alternative embodiment of an array having elements curved in three dimensions.

DETAILED DESCRIPTION OF THE INVENTION

[0025] FIG. 1 shows a line source 10 curved circularly. This type of source produces a constant wide beam pattern over a broad frequency band. The beamwidth (BW) of the pattern is controlled by the active area arc length s and angle (θ) coverage when the aperture radius r is much greater than the acoustic wavelength λ. The -6 dB beamwidth (BW -6dB) is approximately equal to the total angle (θ) in degrees when $r > 8\lambda$. The beamwidth in degrees of a lobe is ordinarily measured from where the signal falls off by 6 dB on either side of the main lobe. As known in the art, this is the -6 dB beamwidth. In source 10, the -6 dB beamwidth (BW -6dB) is approximately equal to the angle (θ) of the source 10 in degrees when $r > 8\lambda$.

[0026] FIG. 2 shows this line source modeled as an array 12 of discrete point sources 14 along an arc. This array 12 has one point source 14 at every degree from +55° to -55° (110° total and 111 point sources) and a radius of 13.75 wavelengths ($r = 13.75\lambda$). In FIG. 2, the x-y axes are normalized by the acoustic wavelength. This will generate a fan-shaped beam pattern 16 that is approximately equal to 110° wide at 6-dB down points 18 as shown in FIG. 3. The beam pattern frequency is at $f_o = c/\lambda$, where c is 1,500 m/s, the sound speed in water. The point sources 14 in the model all have the same uniform amplitude weighting coefficients of 1. The beam pattern has an oscillatory behavior known as ripple or scalloping (resembling a scallop clam shell shape) which is described mathematically as the Gibbs Phenomenon. The beam pattern 16 shown here has constructive and destructive interference caused by the path lengths of the point sources 14. A continuous line source would smooth, or average, these far-field pressures and have an ideal oscillatory pattern.

[0027] In order to form a beam pattern of a desired shape, amplitude shading is applied to the point source model given in FIG. 2. As an example, one desired beam pattern 20 is provided in FIG. 4. Beam pattern 20 is obtained by applying logarithmic shading to each point source element 14. Utilizing this shading, the amplitude level provided to the element 14 drops 1 dB for each degree from 40^0 to 0^0 as shown in FIG. 5. In the range of 55^0 to 40^0, the amplitude is 0 dB or value of unity in order to maintain the 45^0 beam in FIG. 4 without any attenuation. This results in the beam pattern shown in FIG. 6.

[0028] In the prior art, element amplitude shading was used to obtain the desired beam pattern. Typically, an uncurved linear array of transmitters is used. Beamforming is performed by providing amplitude weighted and timed signals to each element of the array. This results in complex wiring and electronics because it requires that each element be separately addressable.

[0029] The current method utilizes active area shading instead of amplitude shading. In this method the active radiating surface area of the array element is designed to have an area in accordance with that of the amplitude coefficients chosen to generate a particular beam pattern shape. Signal delays are given by the element's relative positioning along the curved array. This positioning gives constructive or destructive interference among the elements of the array.

[0030] Utilizing the beam pattern of FIG. 4, the case of the logarithmic amplitude shading values in FIG. 5 gives an array 22 as shown in FIG. 7. This array has the appearance of a curved bowtie or an hourglass. End portions 24 of array 22 have a larger area as required by the beam shading function given in

FIG. 5. Center portion 26 of array 22 has a much smaller area to give the attenuation desired at the center of the array. A sectional view along line 8—8 is given in FIG. 8. Array 22 includes transduction material 28 sandwiched between electrodes 30 and 32. Transduction material can be a continuous type of transducer material such as piezoelectric polymers. These include PVDF, 0-3 piezo-rubber, and 1-3 piezo-composites, which are semi-flexible continuous sheets. As can be seen in the sectional view, foil electrodes 30 and 32 are deposited, or etched, right on the surface of the transducer material. (FIG. 8 is not to scale, and electrodes 30 and 32 are much thinner than shown.) The use of area shading allows the same electrical drive voltage to be applied to all of the elements in this array, eliminating complex wiring and sonar beamformer electronics.

[0031] For modeling and fabrication, this array could be made more practical by discretizing the continuous array 22 of FIGs. 7 and 8 into a more practical array 34 having discrete sub-arrays 36, 38, 40, 42 and 44 of transducer elements as shown in FIG. 9. The areas of the sub-arrays determine the sound pressure level (SPL) that is produced within the coverage angle of the sub-array. Array 34 in FIG. 9 includes nine sub-arrays that are positioned to direct the energy into a fixed coverage angle. As an example, in FIG. 9, sub-array 44 with area A_1 will radiate full sound pressure level P_1 in the 55^0 to 36^0 angle coverage in order to maintain the 45^0 beam without attenuation. Sub-array 42 with area A_2 will radiate a 10-dB reduction in sound pressure level P_2 for the 35^0 to 26^0 angle coverage, thus $A_2 = 0.316*(A_1)$. Sub-array 40 area A_3 will radiate a reduced 20 dB in SPL in 25^0 to 16^0 angle coverage by area $A_3 = 0.1*(A_1)$. Sub-array 38 area A_4 will radiate a reduced 30 dB in SPL in 15^0 to 6^0 angle coverage by area $A_4 = 0.0316*(A_1)$. Sub-array 36 area A_5 will radiate a reduced 40 dB in SPL in 5^0 to 0^0 angle coverage by area $A_5 = 0.01*(A_1)$, which is repeated as subarray 36′ having angular coverage of 0^0 to -5^0 on the right side of the array 34.

[0032] FIG. 10 is a cross-sectional view of array 34 taken along line 10-10 of FIG. 9. Sub-arrays 36, 36′, 38, 38′, 40, 40′, 42, 42′, 44, and 44′ are shown in cross-section. Each sub-array comprises transducer material 46 in electrical contact between a first electrode 48 and a second electrode 50. Transducer material 46 can be any piezoelectric or ferroelectric transducer material known in the art. A function generator 51 or other electronics is joined to all of the elements of the array. This embodiment allows for transducer materials that are available in flat geometries and/or those that are limited to certain sizes by costs or physics.

[0033] The acoustic output power for an electro-acoustic transducer is the acoustic intensity multiplied by its radiating surface area ($W_o = I_o \times A$). Its electrical input power, W_{in}, and acoustic output power, W_o, are related by the electro-acoustic efficiency of the transducer by $\eta_{eff} = W_o/W_{in}$. For a transducer that is 50% efficient, its acoustic output power is one-half of the electrical input power. For a 100% efficient transducer, input and output power are equal. Sonar transducer efficiencies typically range between 50% and 90% depending on the design type. Array 34 shown in FIG. 9 has nine sub-arrays, each with its own surface area. Total area is $A_T = 2*(A_1) + 2*(A_2) + 2*(A_3) + 2*(A_4) + A_5$. If all of the sub-arrays were of the same length and width as A_1, the array would produce a fan-shaped beam pattern similar to that of FIG. 3. The total surface area would be $A_T = 9*(A_1)$, with the acoustic output power being nine times that of A_1. The total electrical input power would also be nine times greater than A_1 because $W_o = \eta_{eff}W_{in}$. Comparing this with the area shaded design in FIG. 9, where $A_1 = 1$, $A_2/A_1 = 0.316$, $A_3/A_1 = 0.1$, $A_4/A_1 = 0.0316$, and $A_5/A_1 = 0.01$; the total area for the shaded design is $2.9*(A_1)$. The area of the shaded design is approximately one-third less than the area of the equal area sub-arrays array and will require approximately one-third less electrical input power.

[0034] FIGS. 7-10 described a one dimensional transducer array concept that produced a shaped acoustic beam pattern that directs acoustic energy in the ± 45° direction with depressed acoustic energy at 0°. By duplicating this array and rotating the elements so that they are orthogonal to the pre-existing array, a two-dimensional transducer array 52 is developed as shown in FIG. 11. Array 52 produces shaped beam patterns in two planes. A more practical two dimensional array 54 is shown in FIG. 12. To maintain the sub-array area ratios, the widths of the outermost sub-arrays 42 and 44 having areas A_1 and A_2 would need to be increased.

[0035] This concept can be expanded further into arrays having sub-arrays oriented at any angle that evenly divide 360°. Ultimately, this leads to the embodiment shown in FIG. 12. Array 56 is composed of four conical sections assembled from truncated cones of various base diameters, stacked on one another. The conical sections gradually decrease in size from bottom to top with an active disc on top. The outer surface of each cone is slanted to a particular angular direction.

[0036] Array 56 produces a conical beam pattern that is depressed in the middle in accordance with the surface areas and slant angles chosen. Rectangular piston functions cannot be used to model array 56 as in array 34 and arrays 52 and 54. Instead, each of the conical sections has been modeled as a discrete baffled piston. Each of the piston functions is tilted and twisted to form the conic sections.

[0037] As briefly described above, these arrays could be fabricated from many different transduction technologies: PVDF piezoelectric polymer sheets, 0-3 piezo-rubber sheet, 1-3 piezo-composite n x m matrix, or Tonpilz transducer n x m elements. PVDF or co-polymers, (polyvinylidene fluoride trifluoroethylene) (P(VDF-TrFE)) are piezoelectric polymers available in thin sheets (up to 0.50 mm) and are more suited to hydrophone material than to projectors. These materials are available in continuous sheet forms and are semi-flexible; and their surfaces are coated with copper or silver that act as the electrode. Piezo-rubber materials have particles of piezoceramics suspended in a rubber-like matrix available in thicker sheets (3.30 mm). These are also more suited to hydrophone material than to projectors. These materials are available in continuous sheet forms, are semi-flexible, and their surfaces are coated with copper or silver that act as the electrode. The 1-3 piezo-composite material consists of thin piezoceramic rods aligned parallel to the poling direction and imbedded in a polymer filler (epoxies and polyurethanes). Their surfaces are coated with copper or silver that act as the electrode. These are also available in sheet form, are semi-flexible, and are suited to both hydrophone and projector material. Each piezoelectric rod forms an n x m matrix that could be used to fabricate a sub-array. Bending or forming 1-3 piezo-composite into a curved surface over solid ceramic material is one of its major advantages, though induced stresses and geometric distortion can be a challenge. The Tonpilz or Langevin type transducer designs are layered structures of metal piston, piezoceramic, and metal tail mass, which lowers the resonance frequency significantly compared to the 1-3 piezo-composite rod. These transducer elements have a lower mechanical Q_m, more surface area, are more efficient, and transmit more acoustic energy than a piezoceramic rod. A sub-array could be made up of n x m elements of these Tonpilz or Langevin type transducer elements.

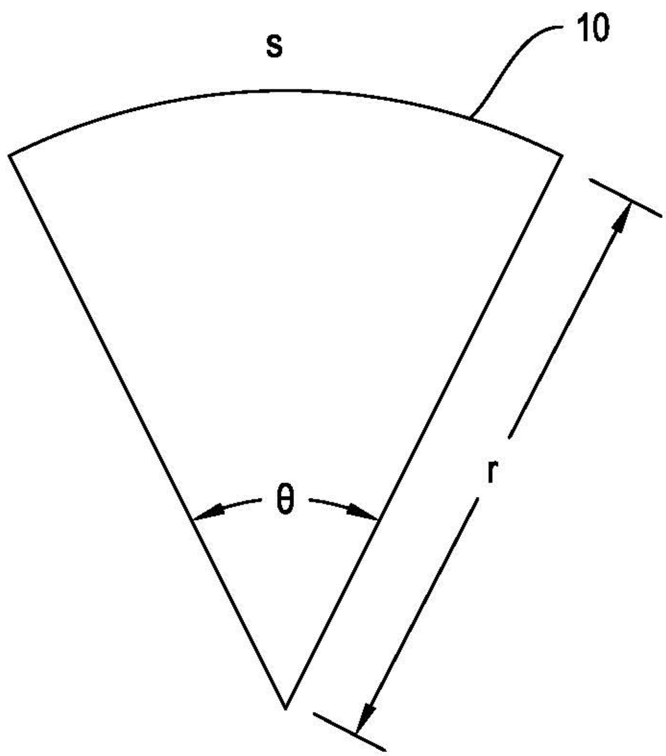
[0038] It will be understood that many additional changes in the details, materials, steps and arrangement of parts, which have been herein described and illustrated in order to explain the nature of the invention, may be made by those skilled in the art within the principle and scope of the invention as expressed in the appended claims.

[0039] The foregoing description of the preferred embodiments of the invention has been presented for purposes of illustration and description only. It is not intended to be exhaustive, nor to limit the invention to the precise form disclosed; and obviously, many modification and variations are possible in light of the above teaching. Such modifications and variations that may be apparent to a person skilled in the art are intended to be included within the scope of this invention as defined by the accompanying claims.

METHOD FOR DESIGNING AN ACOUSTIC ARRAY

ABSTRACT OF THE DISCLOSURE

A method for designing an acoustic array includes establishing a desired beam pattern, acoustic wavelength and beamwidth for the array. Geometric parameters are calculated from these constraints. The array is modeled as a plurality of elements positioned in accordance with the geometric parameters. An amplitude shading function is calculated. An array of acoustic elements is constructed having an area calculated from the calculated amplitude shading function. An acoustic array designed by this process is further provided.


s
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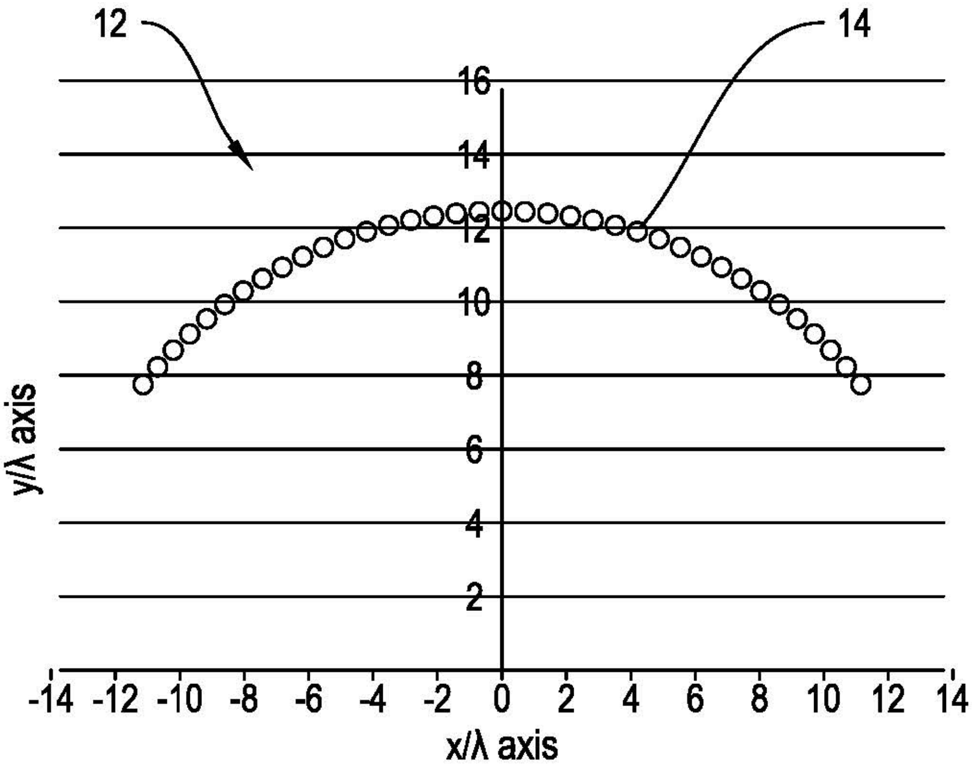
θ
r

FIG. 1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14
16
14
12
10
8
6
4
2
y/λ axis
-14 -12 -10 -8 -6 -4 -2 0 2 4 6 8 10 12 14
x/λ axis

FIG. 2

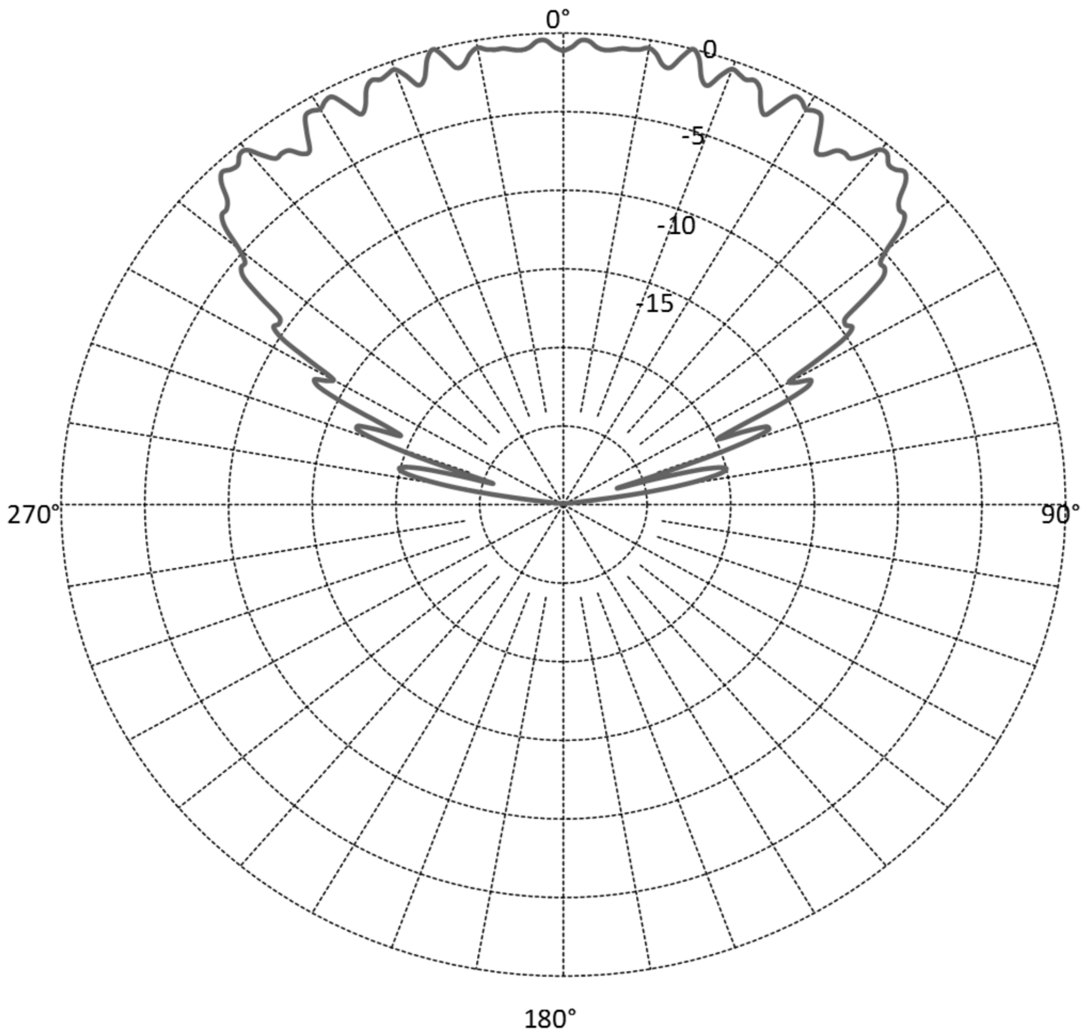


FIG. 3

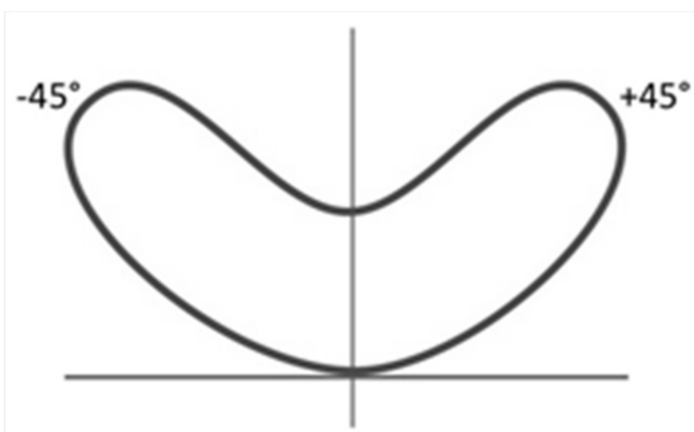
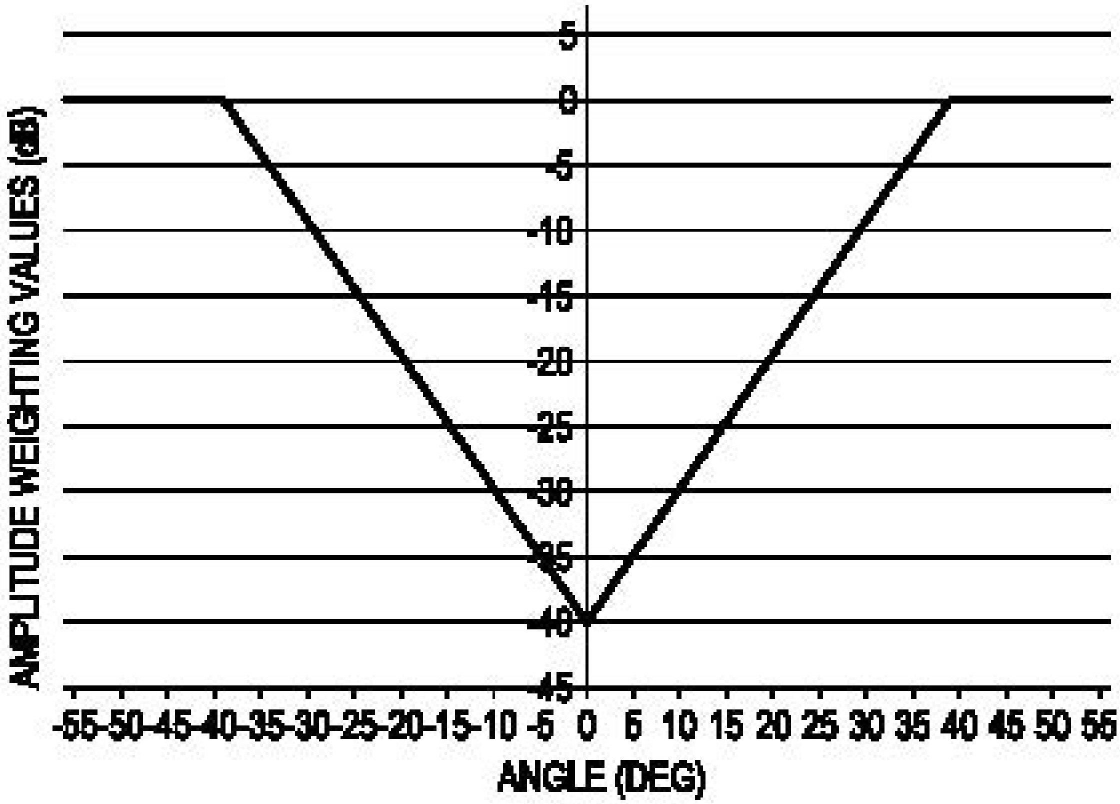
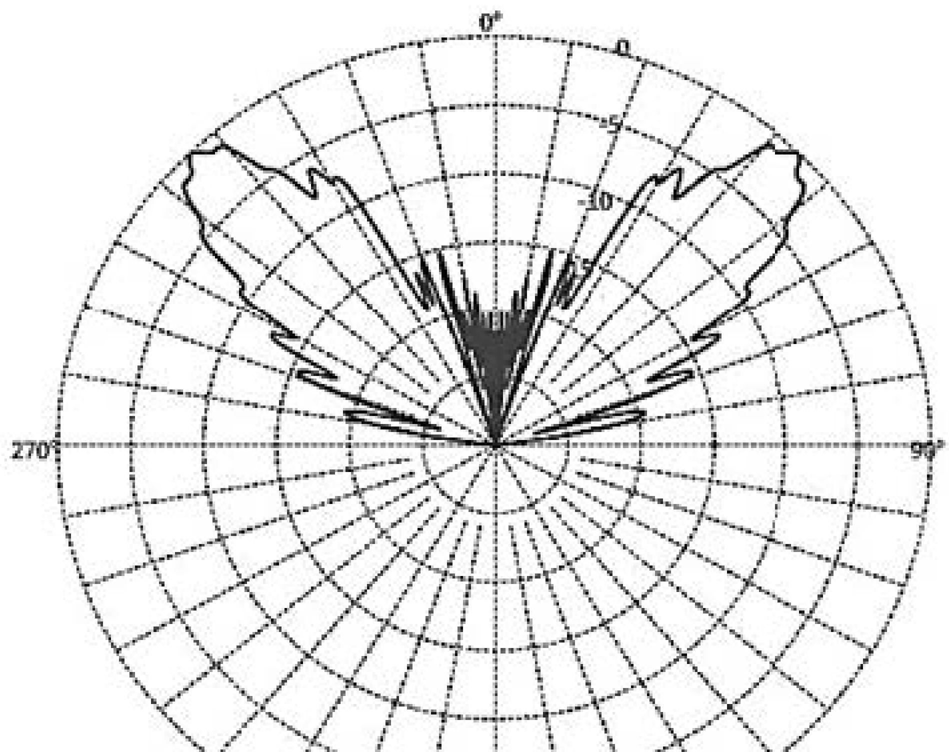


FIG. 4



AMPLITUDE WEIGHTING VALUES (dB)
5
0
-5
-10
-15
-20
-25
-30
-35
-40
-45
-55 -50 -45 -40 -35 -30 -25 -20 -15 -10 -5 0 5 10 15 20 25 30 35 40 45 50 55
ANGLE (DEG)

FIG. 5



0°
0
-5
-10
90°
270°
180°

FIG. 6

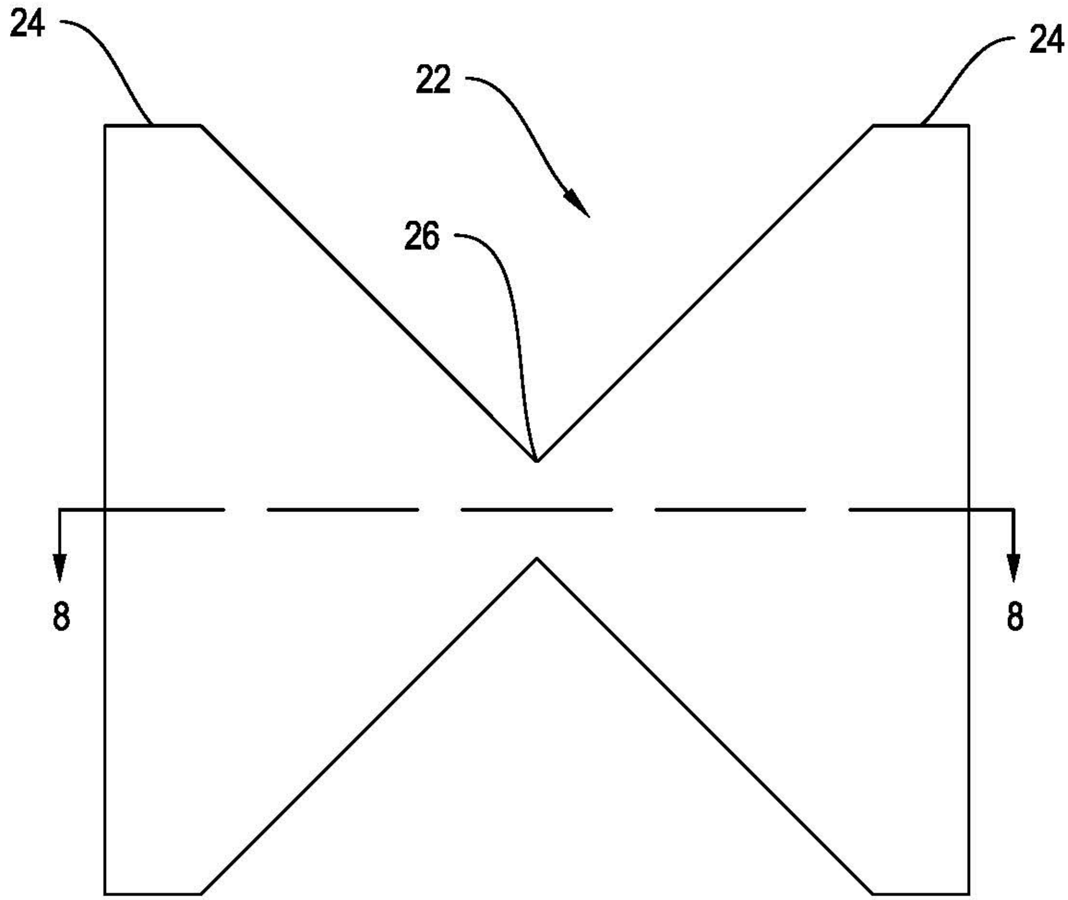


FIG. 7

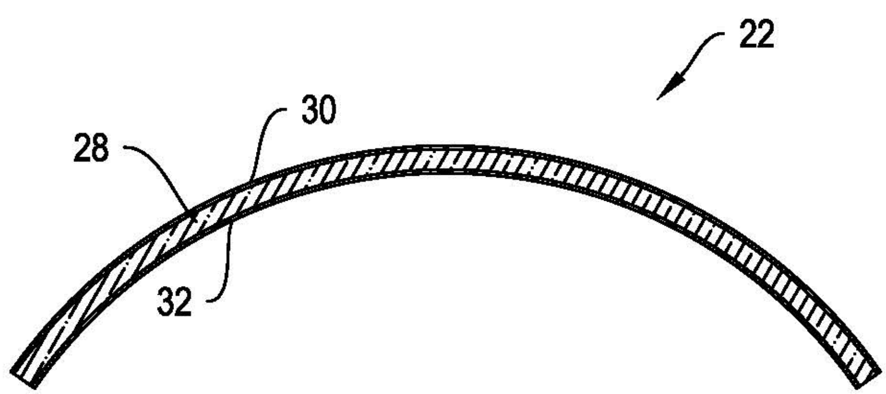


FIG. 8

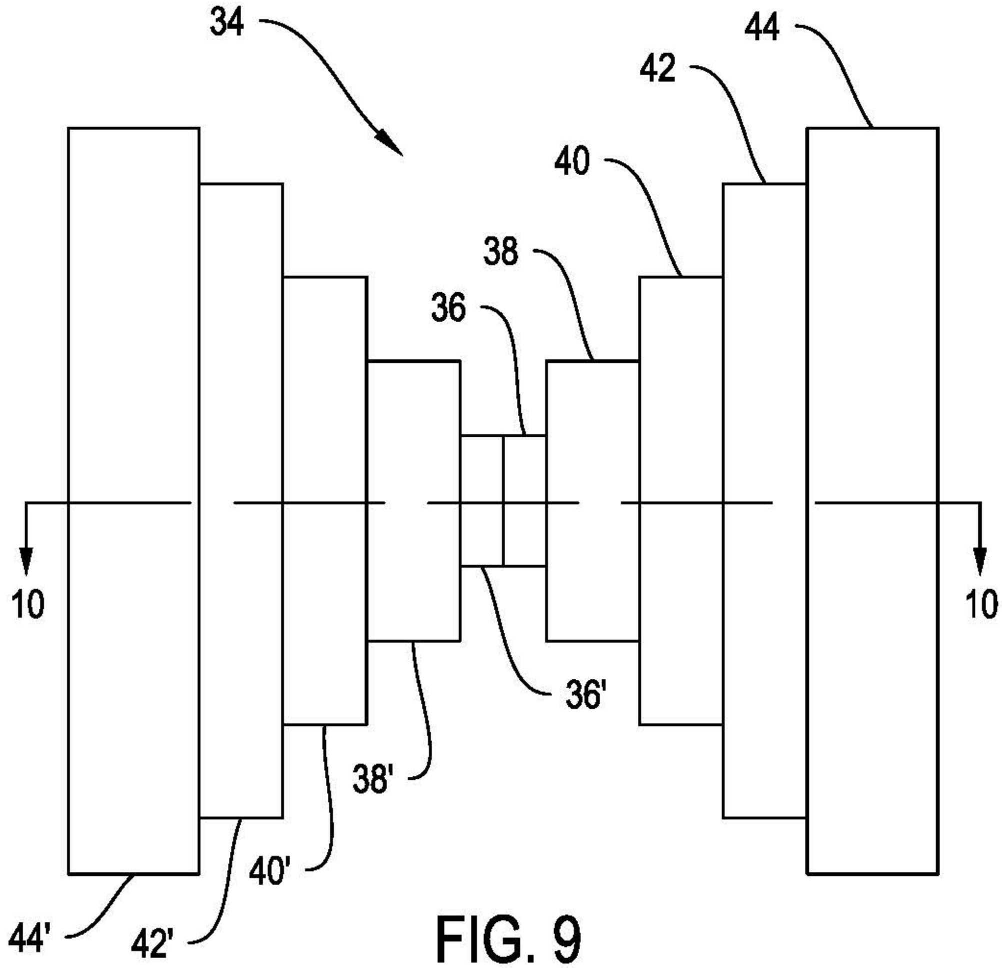

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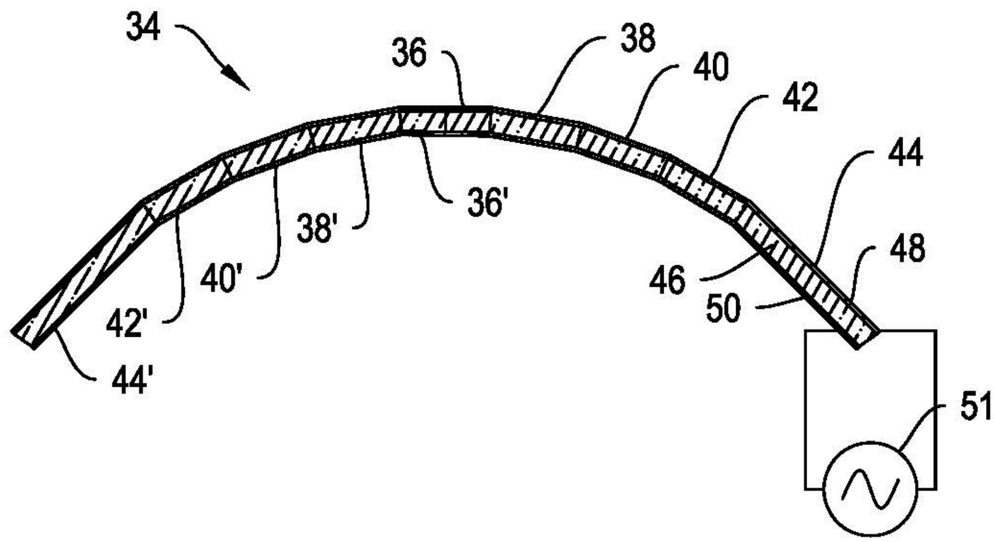
FIG. 9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44'
51

FIG. 10

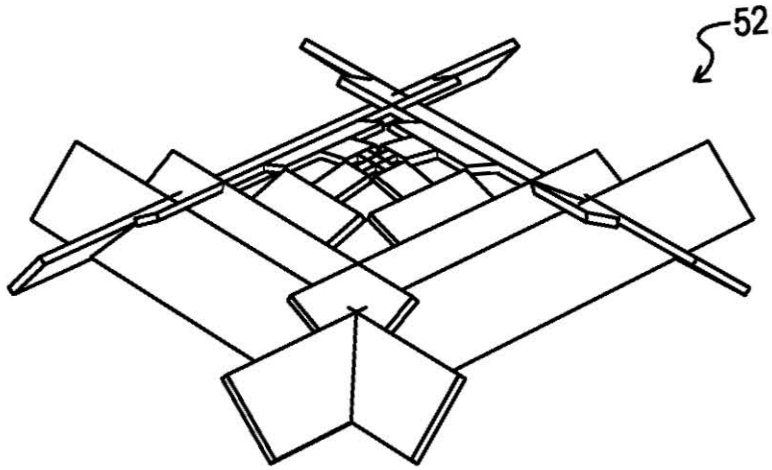

FIG. 11

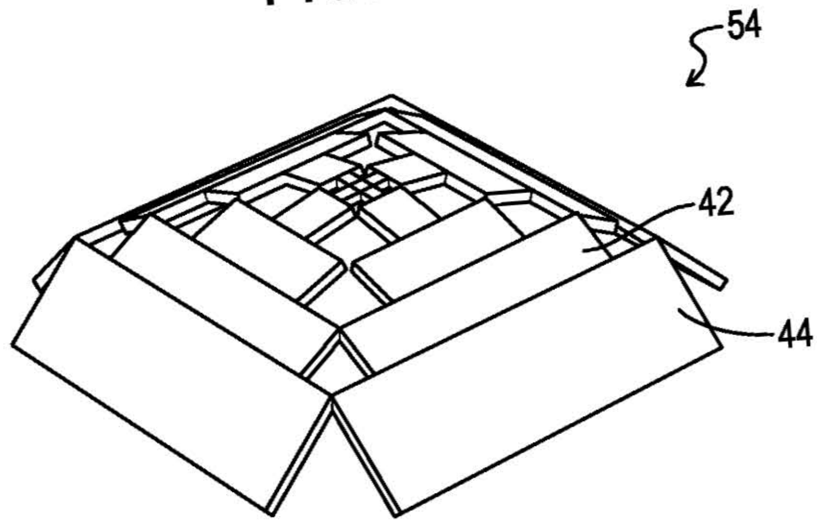

FIG. 12

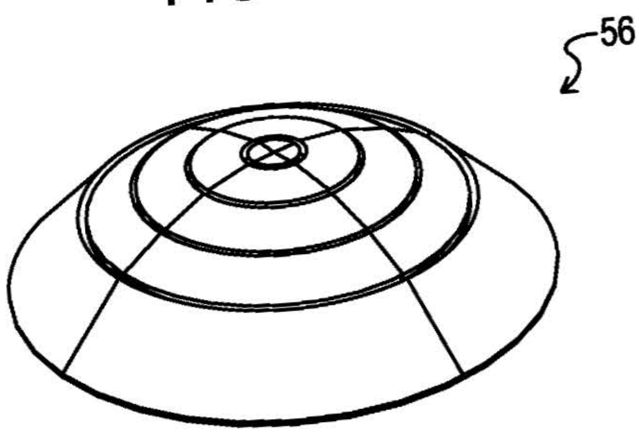

FIG. 13